MACHINE PROTECTION STRATEGY FOR LHC COMMISSIONING AND OUTLOOK FOR FUTURE CHALLENGES

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Abstract

During Run 2, when operating at $6.5\ \mathrm{TeV}$ and $25\ \mathrm{ns}$ bunch spacing, the LHC will accelerate and store beams with an energy of up to $372\ \mathrm{MJ}$. A very tiny fraction of this beam can cause severe damage to accelerator equipment if the energy is released in an uncontrolled way. The note addresses the machine protection considerations for the initial commissioning with and without beam and discusses the required (re-)qualifications for subsequent changes of beam/optics parameters during the run. The definition of the new setup beam intensity - impacting commissioning and later operation and machine developments - is recalled. The note will conclude with an outlook on future challenges with respect to machine protection in view of the injector upgrade and HL-LHC.

INTRODUCTION

After a long shutdown of about 2 years the LHC will start in 2015 producing proton-proton collisions at the new beam energy of $6.5\ \mathrm{TeV}$. The procedures to qualify the machine protection system functionality are being reviewed. The new definition of the maximum intensity allowed in the machine for setup and loss map qualification at the new top energy is presented.

The preferred option by the experiments is the use of $25\ \mathrm{ns}$ bunch spacing filling. In 2012, $50\ \mathrm{ns}$ bunch spacing was used. This has special importance during the intensity ramp-up. Shorter space between bunches may increase electron cloud and this can generate beam emittance growth and increase of beam losses. This note describes the strategy to qualify the machine for the setup with nominal bunches and outlines the different steps during the intensity ramp-up.

On-going studies related to Machine Protection (MP) aspects at injection and an overview of future challenges for High Luminosity LHC with brighter beams will be described in the last section.

MACHINE PROTECTION PROCEDURES

Machine Protection procedures describe all the tests that need to be done by each sub-system in order to qualify its machine protection functionality. A total of 11 procedures are being reviewed before the re-start, see Table 1. In particular, the periodicity of the tests has been addressed as well as the definition of the steps with beam.

Table 1: List of current Machine Protection procedures.

EDMS Nb.	**System**
LHC-OP-MPS-002	Collimation
LHC-OP-MPS-003	Injection Protection
LHC-OP-MPS-004	Beam Interlock
LHC-OP-MPS-005	Powering Interlock
LHC-OP-MPS-006	Vacuum
LHC-OP-MPS-007	Beam Dump
LHC-OP-MPS-008	FMCM
LHC-OP-MPS-009	BLM
LHC-OP-MPS-010	Warm Magnet Interlock
LHC-OP-MPS-014	Software Interlock
In progress	FBCCM

Many systems have been intensively upgraded during the LHC long shutdown, including key elements on the MP chain, like the Quench Protection System (QPS), Beam Loss Monitor (BLM) System and the Collimation System. In several cases, relocation and recabling of several interlock units occurred. For this reason the machine needs a full revalidation during commissioning as for the initial start up.

In order to perform these tests each sub-system should be operationally available and the dependences with other systems as for example LHC Software Architecture (LSA) database, Safe Machine Parameters (SMP),etc. confirmed. The tests without beam include the verification of the input connections to the Beam Interlock System (BIS), the proper triggering of a beam dump from each possible interlock and the correct propagation of the beam interlock signal.

Validation with beam, like loss maps and asynchronous beam dumps are also part of these procedures and will be discussed later.

INITIAL SETUP STRATEGY

The initial setup strategy was outlined in [1]. The first injections at $450\ \mathrm{GeV}$ will be done with pilot bunches ($10^9\ \mathrm{p}$) but a reference machine with a well-established orbit will have to be done with nominal bunches ($\sim 10^{11}\ \mathrm{p}$). This will be followed by collimator alignments, collimator settings validation and LBDS asynchronous beam dump tests.

Definition of Setup Beam Flag

The setup beam flag (SBF) is a parameter used in operation defined to allow the mask of several interlocks. This

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flag can be used only if the intensity in the machine is smaller than a certain limit.

It is considered to be safe when the beam intensity is below the Copper damage limit. This is 1×10^{12} protons at 450 GeV. A scaling with energy shown in Eq. 1 is applied in order to get the intensity limit at top energy [2].

$$I\ [\mathrm{protons}] \leq 1 \times 10^{12}\ [\mathrm{protons}] \times \left(\frac{450\ [\mathrm{GeV}]}{E\ [\mathrm{GeV}]}\right)^{1.7}. \quad (1)$$

Eq. 1 gives the so-called *Normal* limit, which at 4 TeV is 2.4×10^{10} p, which is smaller than one LHC nominal bunch. This formula provides a very approximate figure of the damage potential of the beam. It does not take into account time and space distribution of losses, bunch structure and material exposed to damage. It is used here as a pessimistic assumption.

This limit at top energy is below the practical to guarantee the correct orbit and collisions. The main constrains are the need of at least 2 nominal bunches for the setup of collisions in all 4 experiments, the sensitivity of the Beam Position Monitors (BPMs) and the beam scraped during the collimation setup alignment, validation through loss maps and asynchronous beam dump test. For the 4 TeV operation period, two additional levels were defined to allow the needed intensity for commissioning and measurements, the so-called *Relaxed* that was established to allow 1 nominal bunch at 4 TeV and the *Very Relaxed* that allowed 3 nominal bunches at 4 TeV. Notice that these 2 levels used during Run 1 were above the damage limit.

The requirements for setup and validation at 6.5 TeV are now reviewed. Taking into account the requirements for collision, setup, collimation alignments and validation, the proposed limits at 6.5 TeV are:

- **Normal SBF:** 5×10^{11} protons at injection and 1.2×10^{10} protons at 6.5 TeV, which is considered to be safe.
- **Restricted SBF:** 5×10^{11} protons at injection and 3×10^{11} protons at 6.5 TeV. This intensity should be distributed in up to 30 probe bunches (with intensity 1×10^{10} protons/bunch) enforced by a software interlock. This setup could be used for specific machine developments with approved MP document.
- **Setup Beam SBF:** up to 3×10^{11} protons, constant from 450 GeV up to 7 TeV, distributed in fewer bunches, 2-3 bunches. This is a more restricted flag, only used for machine setup and collimation alignment and validation. These numbers were reviewed after the workshop, the updated reference can be found in [3].

The scaling with energy is shown in Figure 1. A constant upper limit to the intensity is also enforced to 0.5×10^{12} protons to account for smaller emittances. Notice that the *Restricted* and *Setup Beam* modes have the same limit on the total intensity, but a software interlock forces the distribution of protons over more bunches.

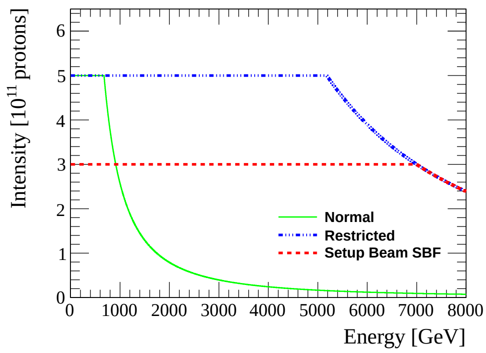

Figure 1: Maximum beam intensity allowed in the machine with the setup beam flag.

MACHINE QUALIFICATION FOR HIGH INTENSITY

The machine must always be qualified after changes in optics, energy, aperture and collimation settings. This is done by analyzing controlled beam losses on the transverse planes, off-momentum losses and asynchronous beam dumps. Table 2 shows the minimum required validation at the start-up. Loss maps and asynchronous beam dump test are required at all stable stages, i.e. injection, flat top, squeezed beam and collisions (or stable beam mode). The betatron loss maps are done exciting each beam independently in the two planes (vertical and horizontal). The off-momentum loss maps are done by changing the RF frequency up and down (both signs also) by a small amount, typically ± 500 Hz. In this case the loss map is done simultaneously for Beam 1 and Beam 2. Validation during dynamic stages as energy ramp and beam squeeze is still to be decided depending on the final choice for beam operation.

Table 2: Minimum required validation after changes in the machine.

Beam Mode	Betatron lossmaps	Off-mom. lossmaps	Asyn. dump
Injection	X	X	X
Flat top	X	X	X
Squeezed	X	X	X
Collisions	X	X	X

Provided that the orbit is stable and that there are no changes and the machine has been qualified for the corresponding collimator settings no additional tests are required. However a minimum validation of the cleaning must be guaranteed and monitored through loss maps at regular intervals. During Run 1 this minimum periodicity was set to 3 months or a technical stop [4].

Intensity ramp-up

The overall intensity ramp-up strategy is presented in [5] and can start after the machine is qualified at low intensity. The restricted Machine Protection Panel (rMPP) will follow the intensity ramp-up, they will analyze each intensity step and decide whether to proceed to the next step. A detailed check list for each intensity step will be filled by the rMPP [6]. The proposed baseline is to have a minimum of 3 fills with more than $20\ \mathrm{h}$ of stable beam running in total for each intensity step but, as it was done in the past, the panel might request to reduce or increase the number of stable beam hours depending on the operational performance.

Experience from Run 1

In 2011 the intensity ramp-up was similar to what it is proposed for Run 2. There were 2 phases, the first being the ramp-up at $75\ \mathrm{ns}$ which happened without major problems. In the middle there were scrubbing runs to reduce the electron cloud. The second phase corresponds to the intensity ramp-up with reduced bunch spacing ($50\ \mathrm{ns}$), see Figure 2. The first steps were also smooth but after some running hours we started to find technical problems such as cooling, controls, etc. We should think about this phase as the debugging and validation period of the new operational settings. It is later, when the intensity exceeded 500 bunches that were observed beam related issues, like vacuum spikes in IR2 and IR8 and the first fast losses due to macro particles falling into the beam [7]. In some cases it was difficult to continue with the ramp-up, it took 41 fills to go from 912 b to 1092 b. Overall, the ramp-up in 2011 took 9 weeks.

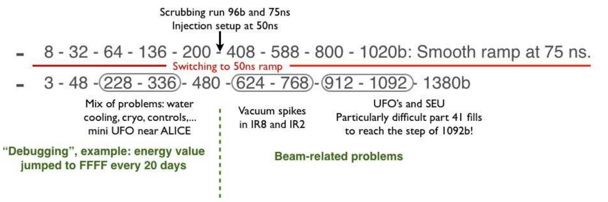

Figure 2: Intensity ramp-up in 2011.

In 2012, however, the ramp-up was very fast, only 15 days. The bunch spacing was $50\ \mathrm{ns}$, identical to 2011, but the main change was the increase of beam energy from $3.5\ \mathrm{TeV}$ to $4\ \mathrm{TeV}$. The shutdown was very short and the machine showed an excellent reproducibility. The number of intensity steps could be reduced to 6, and the number of stable beam running hours for 264 b and 624 b was also reduced to $4-6$ h.

Proposal for Run 2

For 2015 many systems have been changed, including the most relevant for Machine Protection like collimation, beam loss monitors and quench protection system. The debugging of the system will be done during machine checkout and low intensity commissioning, nevertheless an intensity ramp-up at $50\ \mathrm{ns}$ has been proposed to reproduce the same operational scenario as in Run 1 with higher energy ($6.5\ \mathrm{TeV}$). This ramp-up will be done in 9 steps from 50 bunches up to 1380 bunches and is supposed to last up to 3 weeks [5]. At this new energy beam losses are more important and the machine will operate with losses closer to the quench limit of the magnets. Unavoidable phenomena like the interaction of dust particles with the beam (UFO losses) and beam losses due to diffusion and collimation cleaning will have to be addressed and the beam loss monitor thresholds adapted accordingly to allow a safe operation of the machine [8].

After the machine has been trained at $50\ \mathrm{ns}$ there will be the intensity ramp-up at $25\ \mathrm{ns}$. Six weeks are scheduled for this second ramp-up as it is assumed that the system will be completely debugged. For this case 11 steps are proposed from 140 bunches up to 2800 bunches [5]. However, electron-cloud might become more important at $25\ \mathrm{ns}$ and it could be the source of additional beam losses. Depending on the performance during the first intensity steps rMPP could decide the change the number of stable beam hours required before injecting up to 2800 bunches.

ON-GOING STUDIES

In preparation for Run 2 and Run 3 several studies are currently on-going to re-evaluate aperture limitation in the injection areas.

- **LHCb spectrometer crossing and separation bump amplitudes:** In order to solve the problem of the LHCb spectrometer polarity for the $25\ \mathrm{ns}$ bunch spacing the crossing and separation bump amplitudes in IR8 were modified. Table 3 shows the crossing angle and separation for Run 1 and Run 2. The n1 values were re-calculated for Run 1 and Run 2 scenarios and they were found to be very similar. The calculation includes the tilt on Q5 in both IPs ($2\ \mathrm{mm}$ down on the septum side and $1\ \mathrm{mm}$ up on the other side). The critical aperture for the injected beam (kicked or not) is Q5, with $n1 = 4.4$ in IP8 and $n1 = 5.95$ in IP2 which is sufficient margin. For the stored beam (kicked) the critical aperture is D2 with $n1 = 5.5$ for both IP2 and IP8, which is also sufficient [9].

- **ALICE new chamber:** In preparation for High Luminosity LHC (HL-LHC), ALICE is preparing to install a smaller beam pipe during the next LHC Long Shutdown II. The first proposal was limiting the aperture in the experiment to $4\ \sigma$. The beam pipe designed was modified to keep the bottleneck in the arc and to guarantee a minimum aperture of $7.5\ \sigma$ [10, 11].

FUTURE CHALLENGES

LHC has highly overpopulated beam tails. This was measured in dedicated scraping beam tests in 2012 and it was found that at $450\ \mathrm{GeV}$ about $4\ \%$ of the beam is distributed after $4\ \sigma$ [12]. For the nominal LHC this corresponds to $14.5\ \mathrm{MJ}$ of stored energy in the beam tails. The

Table 3: Crossing angle and parallel beam separation in the injection regions for Run 1 and Run 2 [9].

	IP2 Run 1	**IP2 Run 2**	**IP8 Run 1**	**IP8 Run 2**
V-crossing $\mu\mathrm{rad}$	±170	±170	0	-40
H-parallel sep. mm	±2	±2	0	0
H-crossing $\mu\mathrm{rad}$	0	0	∓170	∓170
V-parallel sep. mm	0	0	∓2	∓3.5

situation does not improve with HL-LHC parameters, the stored energy will be almost doubled and thus the beam tail population will be about $30\ \mathrm{MJ}$ assuming similar overpopulated distributions. The collimation system is designed for fast accidental beam losses of up to $1\ \mathrm{MJ}$ [13]. This is of more importance during HL-LHC, with new failures scenarios on the ultra-fast loss time scale, relying on passive protection (collimation system). These are:

- very fast perturbation of beam orbit due to missing long range beam-beam deflection [7],
- ultra-fast failures of crab-cavities [7] and
- injection losses after the injectors upgrade that will reduce the beam size with BCMS scheme [14].

In order to ensure the protection of the machine in the next years there are several studies to improve the cleaning and the monitoring of fast losses. In particular the upgrade on the collimation system [15] with the study of more robust materials and better control of beam tails.

CONCLUSIONS

During LHC long shutdown 1 we took the opportunity to review and update the machine protection procedures that will be followed during the start-up. As a result, the definition of the Setup Beam Flag for the operation of $6.5\ \mathrm{TeV}$ was established, evaluating the needs of different levels of setup beam: for machine developments and measurement and for beam commissioning.

Before moving to higher intensities, the role of the restricted machine protection panel will be re-established and, as it was done in Run 1, they will analyze every step on intensity following the check list procedures. The baseline for moving a step up in intensity is requiring 3 fills with more than $20\ \mathrm{h}$ of stable beam conditions. However, rMPP will keep the flexibility to modify this baseline based on the results of the check list analysis.

Run 2 will provide additional insights on approaching future challenges in Machine Protection with operation at $25\ \mathrm{ns}$ in view of high brightness beams with HL-LHC.

ACKNOWLEDGMENT

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